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Washboard moraines in northeastern North Dakota

Dennis N. Nielsen
University of North Dakota

WASHBOARD MORAINES
IN
NORTHEASTERN NORTH DAKOTA

by

Dennis N. Nielsen

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ABSTRACT

The descriptive term "washboard moraine" has been applied to small transverse till ridges occurring in glaciated regions of North America. Washboard moraines have, in the past, been confused with similar transverse features such as ribbed moraines and De Geer moraines. No previous work had been done on washboard moraines in North Dakota prior to this study. Objectives of this study were to (1) map the distribution of washboard moraines in a selected study area, (2) describe the morphology and composition of washboard moraines, (3) determine the origin for washboard moraines, and (4) compare data obtained in North Dakota with previously published information.

Northern Nelson County, North Dakota, was chosen as the study area. Washboard moraines were mapped, sampled, measured and compared in the field. The structure of selected washboard moraines was determined by using pebble fabric analysis.

Washboard moraines in northern Nelson County are generally 4 to 15 feet high and are spaced 250 to 550 feet apart. The moraines are subdued, discontinuous, irregular ridges paralleling each other. The moraines are composed of slightly gravelly loam. The till has unimodal, bimodal and polymodal grain-fabric distribution; preferred orientations were generally unrelated to regional ice flow direction. Some washboard moraines cross eskers and drumlinoid features. Slopes ranged from 2° to 6° and showed no proximal or distal slope variation.

Based on Nelson County field observation and on studies in Greenland and Alberta, washboard moraines appear to be remnant shear moraines that were deposited from a superglacial position. Evidence of this includes (1) the crossing of some eskers and drumlinoid features by washboard moraines, (2) the discontinuous and irregular shape of washboard moraines, (3) the absence of consistent proximal and distal slope variation, and (4) the preferentially oriented till fabrics unrelated to regional ice flow. The shear moraines were formed by shearing of active ice over stagnant ice in marginal positions, forming debris-laden shear planes. Debris in the shear planes is released by ablation, forming ice-cored shear moraines.

The preservation of shear moraines during deposition is dependent upon the plasticity of the till and the rate of ablation.

WASHBOARD MORAINES IN NORTHEASTERN NORTH DAKOTA

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INTRODUCTION

Washboard moraines are low-relief transverse ridges occurring in many glaciated regions, including North Dakota. They were deposited from Pleistocene continental glaciers and may be considered to be a type of end moraine because they delimit former ice-frontal positions. Other terms, such as, minor moraines, annual moraines, small moraines, ice-crack moraines, cross-valley moraines, winter moraines and De Geer moraines, have been loosely applied to transverse ridges of differing origin.

The primary objectives of this study were (1) to map the distribution of washboard moraines in a selected study area, (2) to determine the general morphology and composition of the washboard moraines, (3) to compare data obtained in North Dakota with previously published information, and (4) to determine the probable origin of washboard moraines in North Dakota.

Previous Work

Transverse parallel ridges have been described in many glaciated parts of Europe and North America. Unfortunately, many investigators have either used different terms for the same feature or have used the same term for genetically different glacial features. Both descriptive and genetic names have been applied to transverse ridges. A listing of the various transverse ridges that are frequently confused with washboard moraines has been made by Prest (1968) and merits discussion below.

Ribbed Moraine

"Ribbed moraine" is a descriptive term used to refer to moraine areas where relatively large-scale transverse lineaments give a "ribbed" pattern to the land surface (Prest, 1968, p. 6). The ridges consist of bouldery till, are up to a mile in length, are 30 to 90 feet high, and have crests 300 to 1,000 feet apart. Typically, the depressions between the ridges contain elongate or multifingered lakes which serve to accentuate the pattern of the ridges. The ridges are usually steep-sided, are gently arcuate to undulating in ground plan, and are in places connected by irregular cross-ribs. Cowan (1968) attributed the origin of ribbed moraine to pushing and overriding of materials by reactivated ice.

De Geer Moraine

"De Geer moraine" is the term applied by Prest (1968, p. 7) to a succession of discrete, narrow ridges ranging from short and straight to long and undulating, which are found only in areas of former lake or sea cover. They have been called "winter moraines" by De Geer, "washboard moraines" by Mawdsley (1936), and "annual moraines" by Norman (1938).

De Geer moraines are generally spaced from a few hundred to a thousand feet apart and commonly display a rather uniform spacing over broad areas (Prest, 1968, p. 7). The ridges are as high as 40 feet and have widths two to three times their height. De Geer moraines are commonly composed of a stony, sandy to silty till with some lenses of contorted clay and silt. The moraines generally have steep slopes mantled with boulders.

Mawdsley (1936) suggested an aqueous origin for the moraines in situations where thinning glacier ice was buoyed up by waters in proglacial lakes causing the ice to crack away in long parallel blocks. Morainic material washed into the cracks left transverse ridges after the ice melted. Norman (1938) proposed that the moraines were features formed during periods when the ice was nearly stationery, generally during the winter, and should therefore be called "annual moraines." Loken and Leahy (1964) concluded that the "small moraines" near Lake Erie in southeastern Ontario were formed by the mechanism suggested by Mawdsley (1936).

Prest (1968) considers cross-valley moraines such as those described by Anders (1963) in Baffin Island to be a variety of De Geer moraine. The cross-valley ridges are more irregular in ground plan and are more closely spaced than De Geer moraine ridges formed in open waters probably due to confinement by the valley walls. Andrews (1963) described cross-valley moraines with heights of 15 to 45 feet, spaced 150 to 200 feet apart.

Sproule (1939) described "recessional moraines" and "ice-crack moraines" in the Cree Lake region, Quebec. They are probably De Geer moraines.

Washboard Moraines

Washboard moraines of the type found in northern Nelson County are termed "corrugated ground moraine" by Prest (1968, p. 5). Prest suggests that the term "washboard," which Mawdsley (1936) first proposed for the transverse ridges in Quebec, be discontinued because it has been applied to De Geer moraines in Quebec, which are descriptively and genetically different from corrugated ground moraine. The descriptive term "washboard moraine" probably should not be abandoned though, because many publications use the term. Until a definitive genetic name can be given, the term "washboard moraine" should be retained.

Prest (1968) described low-relief ground moraine with irregular branching transverse ridges that impart a corrugated or washboard-like pattern to broad areas. The pattern of the corrugated ridges serves to outline the position of former glacier lobes. The ridges are typically composed of till. Prest described ridges in Alberta ranging from 1 to 10 feet in height, a few hundred feet to a mile in length, and spaced from 250 to 900 feet apart. Transverse ridges occasionally merge with longitudinal ridges. Prest suggested they were probably formed by subglacial pushing, thrusting, or squeezing in association with a fracture system or zone of weakness in an ice-marginal zone, and were preserved because of subsequent stagnation of local ice. Table 1 is a comparison chart of washboard moraines and related features. Comparison profiles of washboard moraines, De Geer moraines and ribbed moraines occur in Figure 1.

Washboard moraines are different from ribbed moraines and De Geer moraines in size, form and origin. Washboard moraines are

TABLE 1. Comparison chart of washboard moraines and related features.

FEATURE	RELIEF	LENGTH	SPACING	LITHOLOGY	SLOPES
Washboard Moraines	4-15 ft.	1500-2500 ft.	250- 550 ft.	Till	2°- 6°
De Geer Moraines	10-40 ft.	100-1000 ft.	300-1000 ft.	Till	17°-40°
Ribbed Moraine	30-90 ft.	max. -- 1 mi.	300-1000 ft.	Till	2°-15°

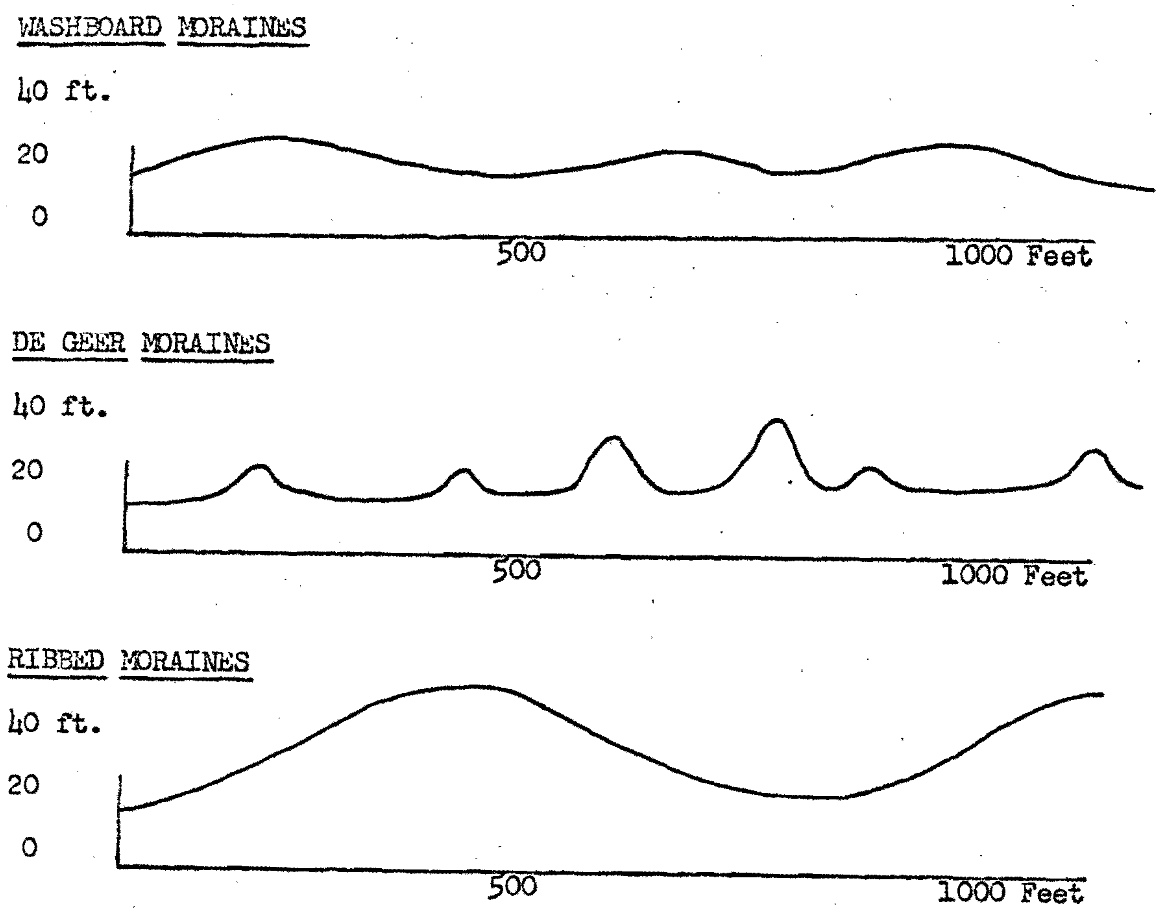


Figure 1. Comparison profiles of washboard moraines, De Geer moraines and ribbed moraine (modified from Gwynne, 1951; Prest, 1968; Cowan, 1968).

small-scale features (less than 15 feet high), whereas ribbed moraines are large-scale features (greater than 30 feet). De Geer moraines can be 10 to 40 feet high, making them small-scale or large-scale. De Geer moraines, however, are very steep sided with slopes up to 40°. Ribbed moraines have moderate slopes of 2° to 15°. Washboard moraines have very gentle slopes of 2° to 6°. De Geer moraines are very narrow compared to washboard moraines and ribbed moraines; their basal width is commonly only two to three times their height, whereas washboard moraines commonly have width-height ratios greater than fifty. De Geer moraines appear to be formed in areas of former lake or sea cover. Ribbed moraines may be formed by reactivated ice that bulldozed unfrozen sediment into transverse ridges. The origin of washboard moraines will be discussed later in this paper.

Washboard moraines have been described in Iowa, Minnesota and South Dakota by Gwynne (1942 and 1951) who called them "minor moraines." The moraines, studied by Gwynne, are similar to those described by Prest in Alberta.

The washboard moraines of the Tiger Hills region, Manitoba, were studied by Elson (1957). By using till fabric analyses, he concluded that the cores of the moraines were comprised of lodgment till. The moraines are superimposed on drumlinoid features and are generally 300 to 500 feet apart. The moraines curve upstream wherever adjacent to large eskers but notnear small eskers. Small eskers are characteristically offset by the moraines and may overlie them (Elson, 1957, p. 77). Elson suggested that the moraines probably formed in a subglacial zone near the ice-margin where active ice thrusted up and over the stagnant ice at the margin which produced a subglacial thickening resulting in a washboard moraine after the ice melted.

METHODS OF STUDY

The selection of an appropriate study area was of importance before any field research could be undertaken. Therefore, aerial-photograph mosaics of several northeastern North Dakota counties were carefully examined in an effort to locate areas of washboard moraine concentrations. Twelve townships in northern Nelson County (Fig. 2) were finally selected as the study area because (1) this area was not previously mapped geologically by the North Dakota Geological Survey, thereby permitting unbiased mapping of the glacial geology, (2) the area was completely glaciated during the Pleistocene, producing a blanket of drift with a washboard moraine density greater than 50 percent, and (3) the area has had minimal modification by post-glacial loess deposition, wind erosion, water erosion or human activity.

During the summer field season of 1967 and 1968 the surface lithologies of all twelve townships in northern Nelson County were mapped at a scale of 3 inches to a mile and later reduced to a scale of 1 inch to a mile. Aerial stereo pairs were used in conjunction with field studies and examination. All passable roads were traversed for field investigation. The lithology of the surface sediments was determined by digging and sugering selected locations in the study area. The North Dakota Geological Survey augered several sites as much as 60 feet in depth for providing subsurface information.

Nelson County washboard moraines were mapped mostly from aerial photographs because surface investigation was restricted by the

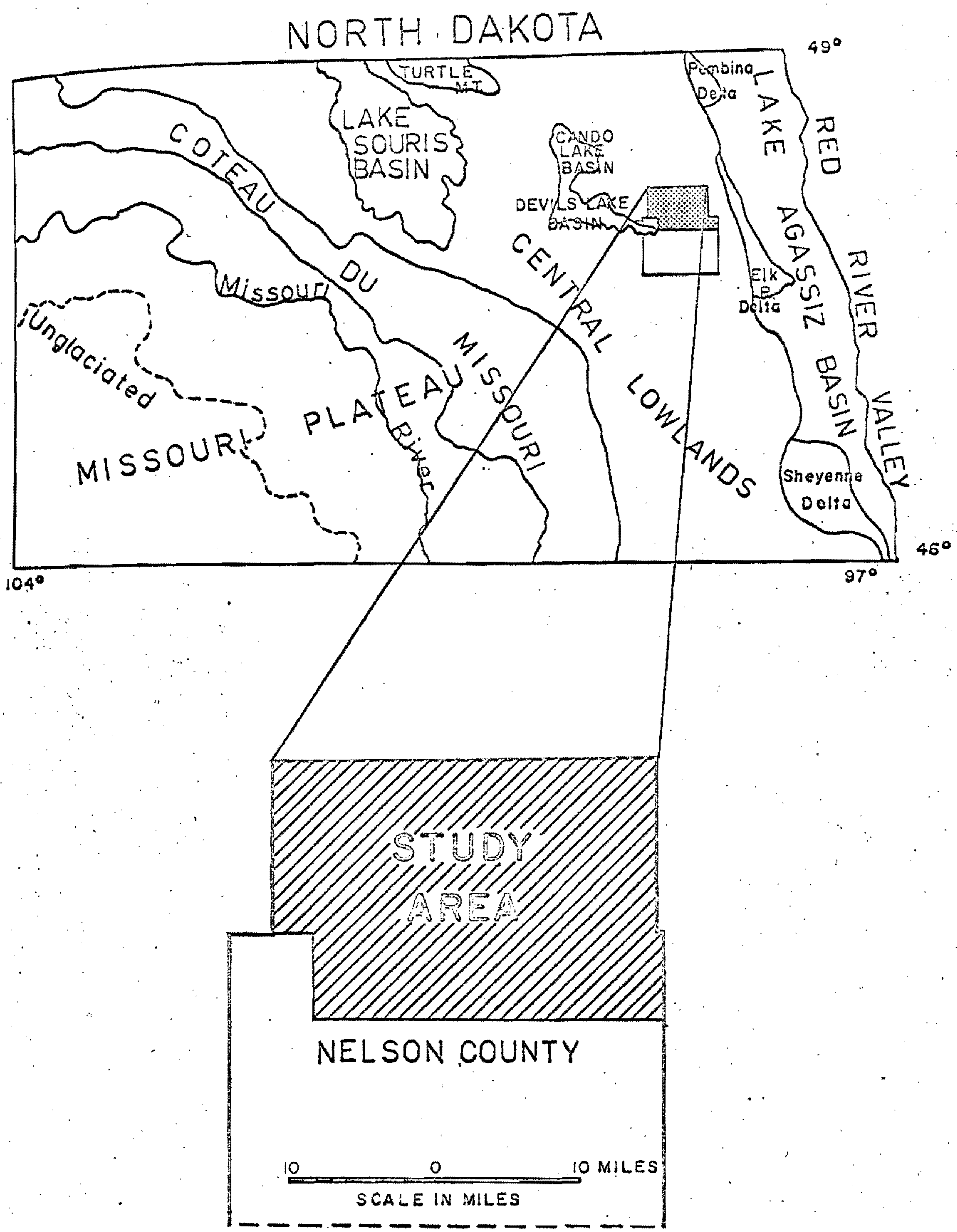


Figure 2. Index map showing the location of the study area in Nelson County and the physiographic subdivisions of North Dakota (after Lemke and Colton, 1958, Figure 1).

low relief of the moraines. When good roadcuts could be found the washboard moraines were examined by (1) measuring height, width, length and slope angles, (2) measuring the bearing of the crests of the moraines from air photographs, (3) sampling sediments for later analyses and (4) determining internal fabric of sediments by measuring the orientation of included pebbles. Twenty horizontal fabric analyses were made on fourteen selected washboard moraines.

Frost commonly extends to depths of 5 feet in North Dakota, resulting in disturbed fabric. Each fabric site was therefore selected to provide the best undisturbed sample. A pit was dug to expose fresh till in each moraine. The orientation of at least fifty pebbles was measured using a compass. Only those pebbles having lengths of 5 to 200 millimeters and length to width ratios of at least 4:1 were measured.

DISTRIBUTION OF WASHBOARD MORAINES

Charlesworth (1957, p. 1151) has described the occurrence of washboard moraines in Finland and in Sweden. The moraines are probably De Geer moraines because of morphology characteristics similar to Canadian De Geer moraines. In all likelihood washboard moraines do exist in Europe but they have not been observed.

Washboard moraines (corrugated ground moraine) are included on the Glacial Map of Canada (1968). The moraines are confined to an area between Calgary to the west and Lake Winnipeg to the east. In general, the southern areas of the Prairie Provinces have the greatest concentrations of washboard moraines.

Lawrence and Elson's (1953, p. 97) reconnaissance survey of the Canadian prairies by means of aerial photographs, disclosed that washboard moraines occupy from 30 to 50 percent of the area from latitude 52° to 49° North, between the Manitoba Escarpment and the Coteau du Missouri in central Saskatchewan.

In Iowa, washboard moraine topography occupies less than half of the Des Moines Lobe (Gwynne, 1942, p. 200). The washboard moraines in Mankato drift is most pronounced in the marginal, more southern part of the lobe.

Only a small part of glaciated South Dakota has reported patterns of washboard moraines (Gwynne, 1951, p. 235). Washboard moraines are most numerous and distinct in eastern South Dakota, in the James River basin, southward from the northeast corner of Jerauld

County, for a distance of approximately 100 miles. Other areas in eastern South Dakota with washboard moraines include Davidson, Hanson, Hutchinson, Bon Homme, Yankton, Sanborn, Spink, Edmunds, McPherson and Faulk Counties. Scattered patches of faint washboard moraines, amounting to no more than 10 square miles, occur in Roberts County, north, east and southeast of Sisseton.

Washboard moraines similar to those in Iowa and South Dakota are present in many southern and central counties in Minnesota, but they occupy no more than a few thousand square miles (Gwynne, 1951, p. 241). Gwynne also indicates that most washboard moraines are found in terrain of low relief. Specific areas include Redwood, Brown, Cottonwood, Watonwan, Martin, Faribault, McLeod, Morrison, Hubbard, Aitkin, Kanabec, Mille Lacs, Pope, Douglas, and Wright Counties. Unfortunately, most of the northern half of the state is forested, making aerial photographs less useful for detecting washboard moraines.

The Glacial Map of Montana (Lemke, Colton and Lindval, 1961) shows washboard moraines in most counties north of the Missouri River and east of the Rocky Mountains, including Sheridan, Roosevelt, Daniels, Valley, Phillips, Blaine, Hill, Chouteau, Liberty and Toole Counties.

Nearly half of the glaciated part of North Dakota contains washboard moraines. The moraines are generally confined to the Central Lowlands (Fig. 2). The individual washboard moraines are such relatively small features that they are shown on glacial maps by lines representing moraine crests instead of discrete individual end moraines. For this reason they are mapped both on ground moraine and end moraine.

Northern Nelson County surface geology is characterized by ground moraine with concentrations of washboard moraines as is shown in Plate 1 (pocket). The moraines are best defined in areas of poorly drained ground moraine with slopes ranging from 1° to 5° and with surface relief generally less than 20 feet. The washboard moraines generally occur parallel to each other, but they may bifurcate and merge with other moraines. The most prominent moraines occur in the townships north and west of Michigan North Dakota (see Fig. 3).

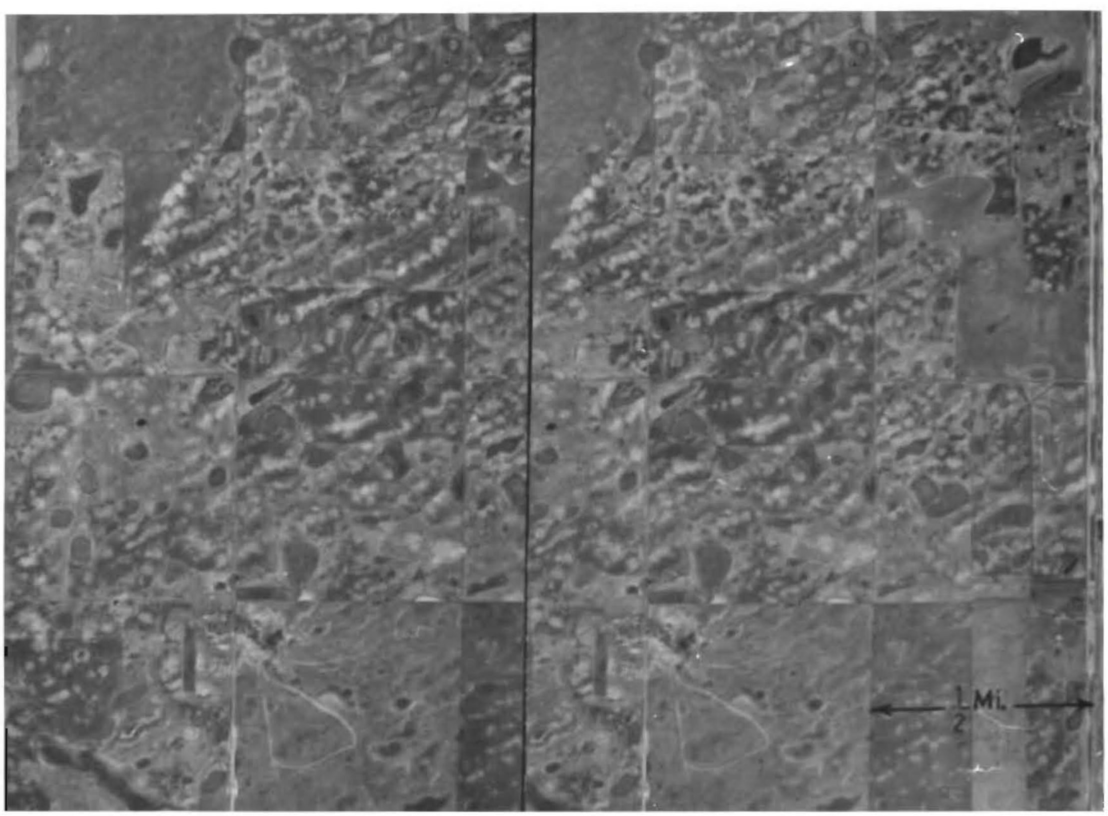


Figure 3. Stereopair of typical washboard moraines in northern Nelson County (Sec. 3, 4, 7, 8, T. 153 N., R. 60 W., 3 miles north and 2 miles west of Lakota, North Dakota). (U. S. Dept. of Agriculture CWM-3W-107 and 108, 6-1-59.)

DESCRIPTION OF WASHBOARD MORAINES

Morphology

The relief between washboard moraine crests and troughs ranges from 4 to 15 feet, averaging about 7 feet in northern Nelson County. Post-glacial modification seems to be an important factor influencing the size and shape of washboard moraines in Nelson County. The moraines are very indistinct or absent in the eastern sections of the study area because of considerable stream erosion, whereas the moraines in the remainder of the study area are generally unaltered because of the absence of streams. Slopewash in northern Nelson County apparently has been minimal since Pleistocene time because of slope stability created by dense prairie vegetation.

Individual washboard moraines in northern Nelson County can be traced on aerial photographs for distances up to 1½ miles but most are only 1500 to 3000 feet long. In the field, washboard moraine crests are not continuous but rather are comprised of a series of moderately straight to arcuate, linear mounds having width to length ratios of approximately 1:5. The parallel arrangement of the mounds provides surface drift with a washboard pattern on aerial photographs. The width of each washboard moraine generally equals the width of inter-ridge spaces.

Individual washboard moraines are generally spaced from 250 to 550 feet apart and number 10 to 20 per mile in northern Nelson County, with an average separation of about 350 feet or 16 moraines per mile.

Figure 4. Surface view of washboard moraines in northern Nelson County (Sec. 25, T. 154 N., R. 60 W.). View looking south.

Slopes range from 2° to 6° on both proximal and distal surfaces. Moraines with steeper slopes are generally spaced more closely than those with gentle slopes.

In transverse profile, a series of washboard moraines are represented by a low amplitude sinusoidal curve (Fig. 4). The sinusoidal profile is best seen in the field along freshly bladed road ditches trending normal to the axes of the washboard moraines (Fig. 5).

Regional Relationships

On aerial photographs, washboard moraines appear to terminate abruptly at vegetational contacts. Vegetation can obscure washboard moraines on aerial photographs by masking the more distinct tonal

Figure 5. Freshly exposed ditch showing the cross-profile of a washboard moraine (NE¼ NE¼ Sec. 11, T. 153 N., R. 59 W.) View looking northeast.

contrasts in the surface soil horizon. Normally, washboard moraines appear distinct on photographs because the moraine crests are light due to removal of some dark organic material in the soil by erosion mostly during cultivation. The swales are dark as a result of thicker organic accumulation and increased moisture content.

Groups of washboard moraines occur throughout northern Nelson County. The groups display a pattern of parallel ridges. The alignment has been used to determine direction of ice flow ever since Mawdsley (1936) interpreted washboard moraines as being formed parallel to the ice margin, normal to direction of ice flow. Ice-marginal irregularities cause the orientation of individual washboard moraines to differ slightly in each group, making it necessary to average the orientation direction of several moraines when regional ice flow direction is determined (Fig. 6).

Figure 6. Oblique aerial view of washboard moraines with slight variation in individual orientation (NE¼ Sec. 15, T. 153 N., R. 59 W.). View looking north.

Plate 1 indicates three primary orientations of washboard moraines in northern Nelson County. Northeast of Michigan the moraines trend approximately N 70°W and gradually change to a N 90°E direction farther north and west. North of Lakota the moraines trend in a general N 45°E direction. An interlobate area (Fig. 7) is shown in Plate

1 approximately 6 miles north of Lakota and is indicated by (1) a meltwater channel, (2) the occurrence of many long, sinuous eskers paralleling the low depressional area, and (3) a change in trend of the washboard moraines from one side of the depressional area to the other indicating two directions of ice flow.

Figure 7. An interlobate area 6 miles north of Lakota, North Dakota. A change in trend of the washboard moraines and the occurrence of eskers and meltwater channels are illustrated (SE¼ Sec. 26, T. 154 N., R. 60 W.). (Army Map Service BE M 28 3487, September 1952.)

Elson (1957, p. 77) observed that washboard moraines in Manitoba always curve upstream near large eskers, but not near small eskers.

Small eskers are offset at the moraines and may cross over them. The eskers and washboard moraines in northern Nelson County do not always have the same relationship as those described by Elson; in some cases, washboard moraines do curve upstream near large eskers and in others they do not. The washboard moraines on the flanks of the large esker (greater than 20 feet high) in the northwest sections of T. 152 N., R. 60 W., curve upstream, but those on the flanks of an equally large esker in the northeast sections of T. 154 N., R. 60 W., do not (refer to Plate 1).

Small eskers, less than 20 feet high, are seldom offset at the washboard moraines in northern Nelson County. Generally the moraines either grade into the flanks of small eskers (Fig. 8) or cross over them (Fig. 9).

Figure 8 shows washboard moraines that grade into the flanks of a small esker, but apparently do not cross it. The orientation of the moraines does not change appreciably where they intersect the esker, and the esker is continuous with no apparent offset segments. If the moraines were continuous and were formed beneath the esker, one could assume that the moraines were formed subglacially or englacially. The subglacial moraines would become draped by esker debris as the ice melted, resulting in a badly deformed and disjointed esker unless the esker stream cut its way through the moraines during deposition. One might expect to see, however, offset esker segments caused by the blocking of an esker tunnel by a large washboard moraine, resulting in lateral diversion of the esker-forming water.

If the washboard moraines illustrated in Figure 8 were formed superglacially rather than subglacially, the esker was probably formed

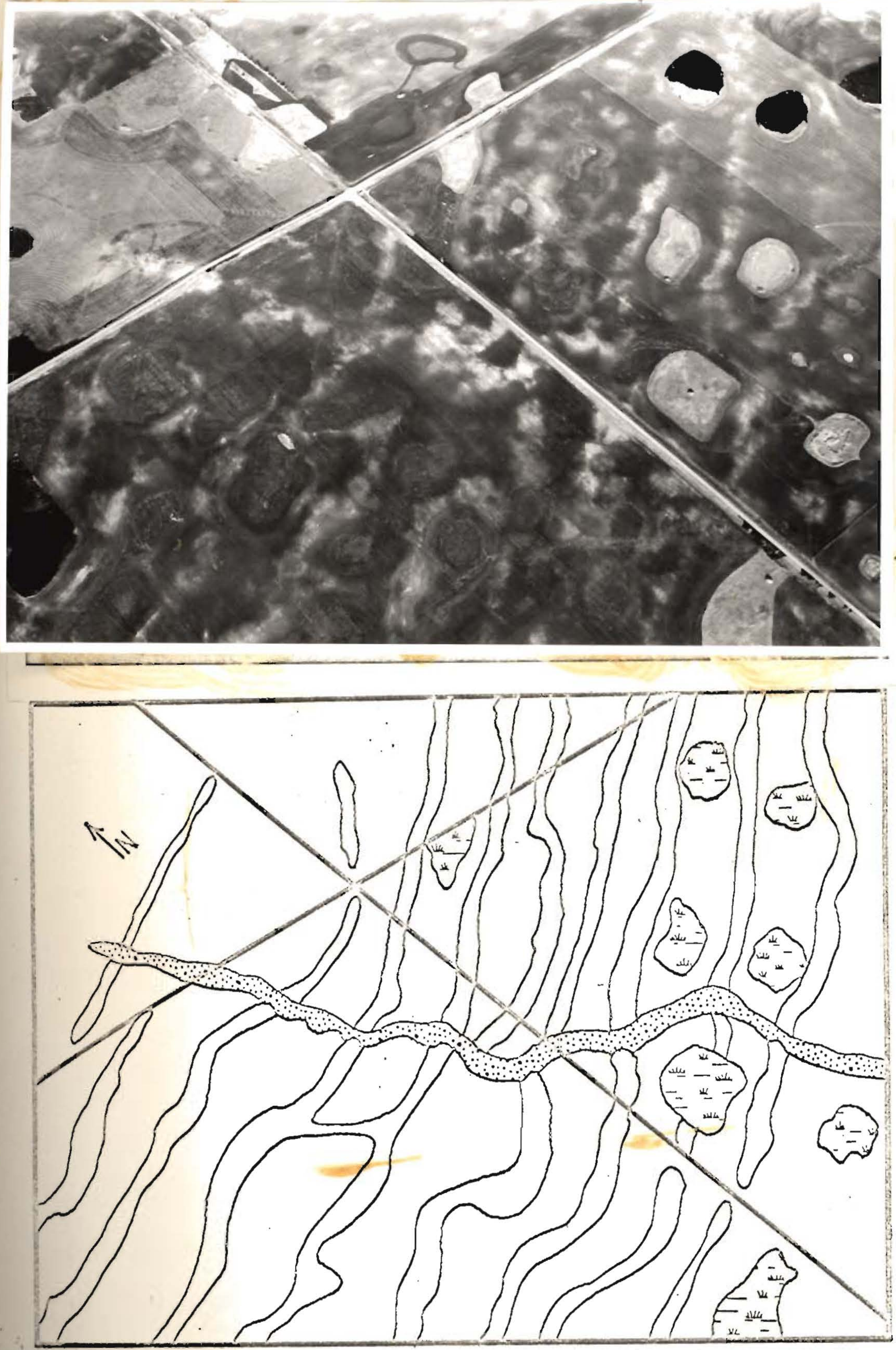


Figure 8. A photograph and comparsion sketch of washboard moraines intersecting a small esker in northern Nelson County.

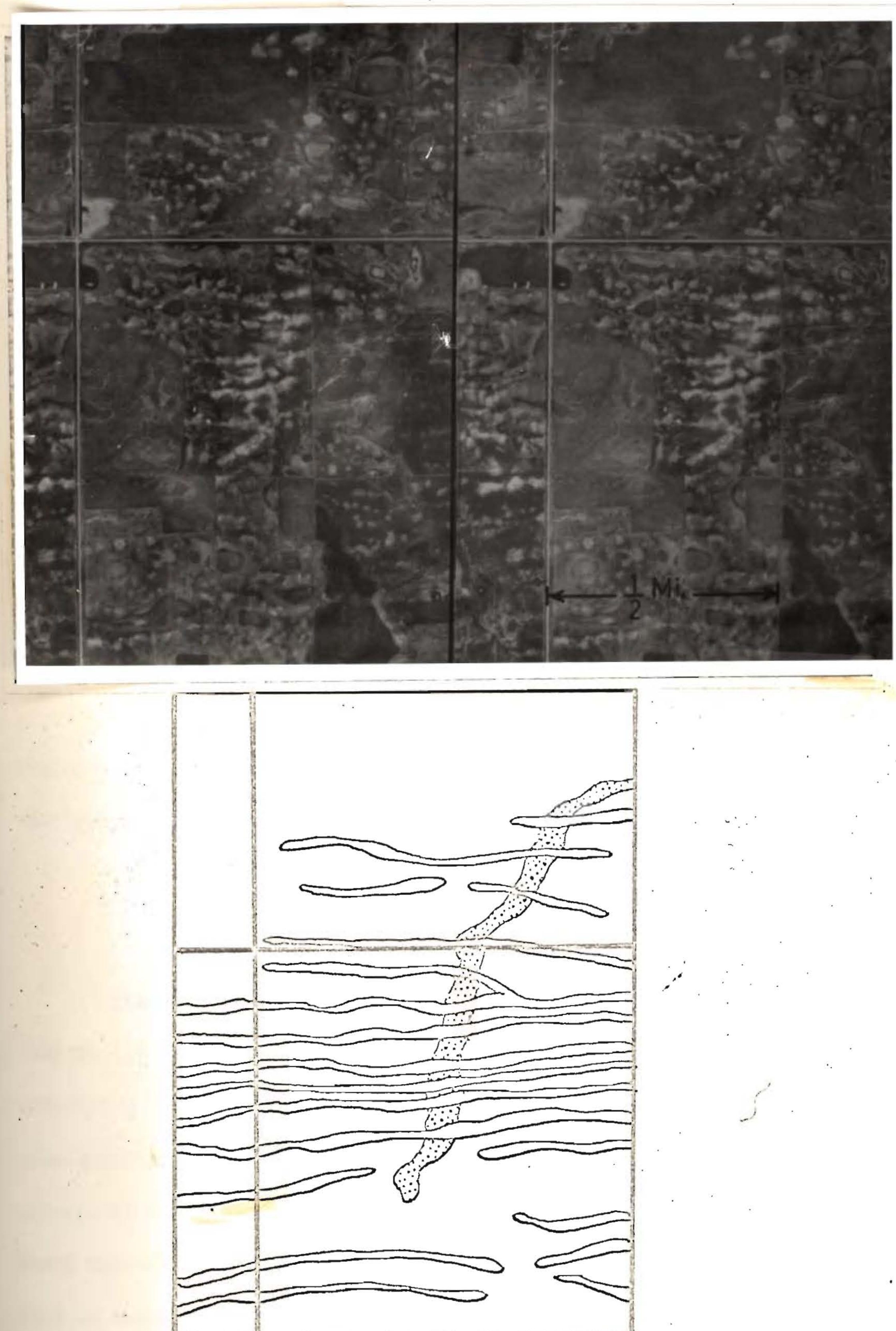


Figure 9. Stereopair and comparison sketch of washboard moraines crossing an esker in northern Nelson County. (U.S. Dept. of Agriculture CWM-3W-162 and 163, 6-1-59.)

subglacially or englacially. The esker was not formed superglacially, because the width between channel banks of the surface stream would progressively widen as ice melted, resulting in lateral erosion of the superglacial washboard moraines. Regardless of whether the esker was subglacial or englacial, it must have been exposed for a short time, otherwise the moraines would have been draped over the esker.

In northern Nelson County there are several examples of washboard moraines crossing eskers, one of which is shown in Figure 9. The esker trends approximately due north and has at least five washboard moraines crossing it. Till averaging 2 feet thick overlies sand and gravel where each washboard moraine crosses the esker, but between the moraine ridges sand and gravel is exposed at the surface with no overlying till.

Washboard moraines are superimposed on drumlinoid features in Manitoba (Elson, 1957, p. 77) and on linear drumlins in southern Nelson County, North Dakota (Sec. 30, T. 149 N., R. 61 W.).

Composition

Lithology

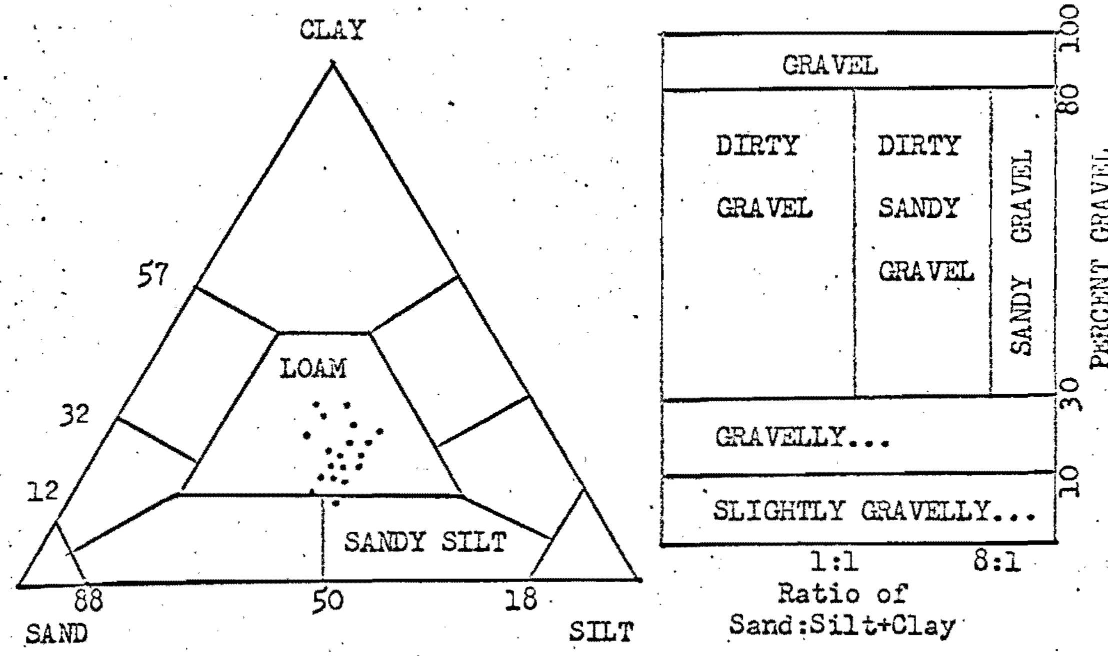
The till of washboard moraine in Nelson County is characterized by (1) a high percentage of shale fragments derived from the underlying Cretaceous Pierre Formation, (2) absence of a platy of fissile structure and (3) a soft, loose consistency. Therefore, the till appears to be ablation till. Till exposures in some areas where washboard moraines are absent exhibits a platy, well-compacted structure that is characteristic of lodgment till.

Sediment samples were taken from all the washboard moraines selected for fabric analysis. Moraine sampling consisted of cutting a fist-sized block of fresh till with all gravel coarser than 1 inch in diameter omitted. Grain-size analyses were made on the samples using pipette analysis as described by Folk (1965, p. 37). Results of the analyses are plotted in Table 2. In most washboard moraines sampled, the till consisted of a slightly gravelly loam.

Two other sediment sample analyses are plotted in Table 2. Sediment sample 1 was taken from a deep roadcut in an area without washboard moraines nearby. The sediment appeared to be a well compacted, fissile till, and is assumed to be lodgment till even though grain size analysis indicates that the till is similar in grain size distribution to the washboard moraine samples. Sediment sample 7 is till taken from a washboard moraine overlying an esker. Grain size analysis suggests a close similarity between sample 7 and other washboard moraines. The lack of appreciable differences in grain size between tills in Nelson County suggests that grain size of ablation and lodgment till is not significantly different. Washboard moraine till cannot be classified as being lodgment or ablation till solely on grain size alone.

Plasticity measurements obtained from engineering reports for Minuteman Missile sites in Nelson County (on file at the North Dakota Geological Survey), show an average liquid limit value of 35 percent and an average plasticity index of 18 percent. Terzaghi and Peck (1948, p. 34) indicate that such average values are characteristic of inorganic clays of medium plasticity. If washboard moraines were supraglacial features, plasticity of the till would be important in re-

TABLE 2. Grain size analyses of washboard moraine sediments from northern Nelson County (Based on North Dakota Geological Survey standard sediment classification).



Sample No.	Location	G.	S.	St.	C.	Classification		
1	SE¼ SE¼ Sec.17, T.154N., R.59W.	4	27	45	24	Sty.	Gvy.	Loam
2	NW¼ SW¼ Sec. 9, T.153N., R.58W.	7	28	31	34	"	"	"
3	NW¼ SW¼ Sec. 3, T.154N., R.59W.	6	39	40	15	"	"	"
4	NE¼ NE¼ Sec.36, T.154N., R.60W.	4	25	35	35	"	"	"
5	SW¼ SW¼ Sec.11, T.153N., R.60W.	9	22	42	28	"	"	"
6	SE¼ NE¼ Sec. 9, T.153N., R.60W.	16	25	38	21		"	"
7	NW¼ NW¼ Sec. 6, T.153N., R.60W.	5	30	44	21	"	"	"
8	SE¼ SE¼ Sec.14, T.154N., R.60W.	3	27	44	25	"	"	"
9	NW¼ SW¼ Sec.23, T.153N., R.58W.	4	26	38	34	"	"	"
10	NE¼ SE¼ Sec. 9, T.153N., R.58W.	1	25	45	39	"	"	"
11	NE¼ NE¼ Sec.28, T.153N., R.58W.	9	27	39	25	"	"	"
12	NW¼ NW¼ Sec.19, T.154N., R.58W.	5	29	42	23	"	"	"
13	NE¼ NE¼ Sec.11, T.153N., R.59W.	5	36	44	14	"	"	S.St.
14	NE¼ NE¼ Sec.11, T.153N., R.59W.	10	28	40	22	"	"	Loam
15	NE¼ NE¼ Sec.11, T.153N., R.59W.	4	35	32	29	"	"	"
16	NE¼ SE¼ Sec.14, T.154N., R.59W.	6	30	41	22	"	"	"
17	SE¼ NE¼ Sec.33, T.154N., R.60W.	2	26	43	28	"	"	"
18	SE¼ NE¼ Sec. 9, T.153N., R.60W.	5	30	41	25	"	"	"
19	SW¼ SW¼ Sec.23, T.153N., R.58W.	3	32	31	34	"	"	"

spect to the morphology and preservation of washboard moraines during deposition. Tills such as found in Nelson County would flow plastically during mass-wasting, resulting in irregular, subdued features. Tills of low plasticity (high sand gravel content) would be less susceptible to mass-wasting during deposition, resulting in a feature with greater relief and greater slope angles.

Structure

The grain fabric of the washboard moraines in northern Nelson County was analyzed to provide information that would be of later use in developing a theory for the origin of washboard moraines. Rose diagrams of all till fabric analyses appear in the Appendix.

Pebble orientation in sediments has been used by such workers as Harrison (1957), Holmes (1941), Glen, Donner and West (1957), Dreimanis (1959), and Elson (1957), to classify tills and determine ice flow direction. Previous work has indicated that lodgment till generally has pebbles preferentially oriented parallel to direction of ice flow, whereas ablation till generally has a more random pebble orientation (Flint, 1957, p. 113).

The fabric determined on distal and proximal slopes may not represent the original fabric because of frost disturbance at such shallow depths. The cores of washboard moraines, however, were generally sampled at depths of 4 feet or more in fresh till, below probable frost disturbance.

Table 3 indicates that of a total of sixteen moraine cores analyzed, eight reveal unimodal distributions. Of the eight unimodal fabric patterns, three have a general preferred orientation parallel

TABLE 3. Table of till fabric measurements from selected washboard moraines in northern Nelson County.*

Site No. and Sediment No.	Location in Moraine	Depth of Analysis	Principal Modes 1	Principal Modes 2	Trend of Wash-board Moraine	Type of Distri-bution
2	Core	4 ft.	N 50 E	none	N 65 W	Unimodal
	Proximal	2 ft.	N 5 W	N 75 W	N 65 W	Bimodal
	Distal	3 ft.	N 55 E	none	N 65 W	Unimodal
3	Core	4 ft.	N 50 E	none	N 90 E	Unimodal
	Distal	2 ft.	N 90 E	0	N 90 E	Bimodal
5	Core	3 ft.	0	N 85 W	N 50 E	Bimodal
6	Core	3 ft.	N 65 W	N 60 E	N 50 E	Polymodal
8	Core	4 ft.	N 85 E	N 10 E	N 80 E	Bimodal
9	Core	4 ft.	N 85 E	none	N 70 W	Unimodal
10	Core	4 ft.	N 35 W	N 35 E	N 65 W	Polymodal
11	Core	4 ft.	N 30 W	N 50 E	N 45 W	Polymodal
12	Core	4 ft.	N 5 W	none	N 90 E	Unimodal
	Distal	3½ ft.	N 30 W	N 90 E	N 90 E	Bimodal
13	Core	3½ ft.	N 75 E	none	N 85 W	Unimodal
14	Core	4½ ft.	N 80 E	N 40 E	N 85 W	Bimodal
15	Core	5 ft.	N 20 W	none	N 90 E	Unimodal
16	Core	6 ft.	N 90 E	none	N 90 E	Unimodal
17	Core	4 ft.	N 50 W	N 60 E	N 55 E	Bimodal
18	Core	5 ft.	N 45 E	none	N 60 E	Unimodal
19	Core	6 ft.	N 75 W	N 5 E	N 75 W	Bimodal

*See Table 2 for location of sites.

to direction of regional ice flow (number 2, 12, and 15). The other five unimodal distributions have a general preferred orientation ranging from 50° to 90° from the direction of ice flow. No consistent preferred orientation was observed for all unimodal distributions.

Bimodal and polymodal distributions are characteristic of the other eight cores. Four of the five bimodal distributions have primary and secondary modes at right angles to each other (samples 5, 8, 17 and 19). Glen, Donner and West (1957, p. 203) suggested that pebbles being deposited in lodgment till first align parallel to direction of ice flow but will in time become aligned transverse to the flow if their axial ratios are less than 15:1. One Nelson County bimodal distribution had a modal separation of approximately 40° whereas all the other bimodal distributions had approximate 90° separation.

Three fabrics have polymodal or random distributions, with weak modes (numbers 6, 10 and 11). Random fabric patterns probably result from extensive alteration of original fabric during and subsequent to deposition. Random fabric patterns may be primarily the result of post-glacial modification by frost, animals or plants.

Modes rather than means from each fabric pattern were used for fabric evaluation in northern Nelson County because of the many fabrics with large standard deviations and strong bimodality. Figure 10 shows six townships in northern Nelson County that contain the washboard moraines used for fabric study. Located on the map are site numbers, trends of washboard moraines, and primary and secondary modes (based on a 180° distribution).

Preferred orientation of pebbles in washboard moraines in Nelson County is so divergent that flow direction could not be determined by pebble orientation. Only four core samples have preferred orientations parallel to ice flow direction (numbers 2, 12, 17 and 18). Site 2 has a preferred orientation approximately parallel to ice flow direction for the core, proximal and distal slopes. Tills with preferred orientations unrelated to the direction of ice flow were probably formed by slumping during deposition from dead ice or by till flowage (Glen, Donner and West, 1957, p. 202); such was probably the

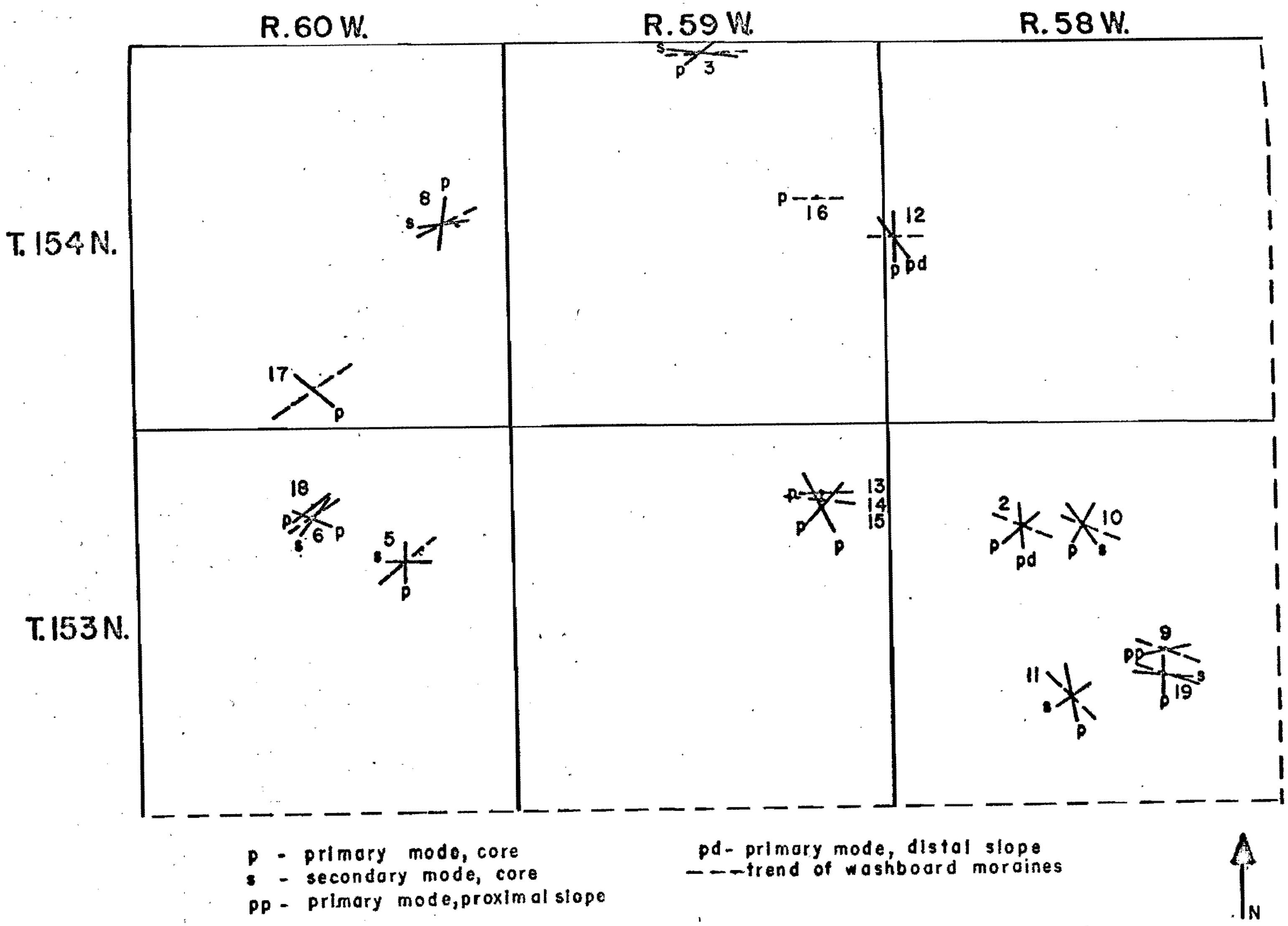


Figure 10. Locations and orientations of selected washboard moraines in northern Nelson County.

case for those preferred orientations in Nelson County having no relation to ice flow direction.

In Manitoba, Elson (1957) made several till fabric analyses on washboard moraines and concluded that the moraines had a core of lodgment till underlying a veneer of ablation drift. Elson based his conclusions on linear statistics applied to unimodal, bimodal and polymodal distributions with standard deviations generally greater than 30°. Denison (1963, p. 147) indicated that cyclical distributions having standard deviations greater than 30° (180° distribution) and strong bimodality should not be evaluated using means because the results would be meaningless. Elson's procedures appear to invalidate his statistical results. The thin veneer of ablation drift may have been frost modified lodgment till.

ORIGIN OF WASHBOARD MORAINES

Previous workers suggest two modes of origin for washboard moraines. Gwynne (1942) indicated that the moraines were marginal accumulations resulting from ice-front oscillation. Elson (1957) and Prest (1968) suggest that washboard moraines are formed by shearing. Both theories may account for the origin of transverse till features, but only one should account for the origin of washboard moraines.

Ice-Front Oscillation

Gwynne (1942, p. 206) proposes that deposition of drift during the summer period of melting at the ice-front was responsible for the marginal accumulation of till. A washboard moraine would form when the ice made a slight seasonal advance pushing the till into a ridge. Actually, a slight readvance would not be necessary for the formation of a transverse till ridge if the ice-front was stationary long enough for superglacial drift to accumulate by mass-wasting. The washboard moraines in Nelson County, however, were probably not formed by such a process because (1) the moraines are moderately consistent in height suggesting a uniform mechanism of formation, (2) the moraines are fairly regularly spaced whereas marginal accumulations would be more unevenly spaced, and (3) the moraines curve around kettles or terminate at their boundaries.

Subglacial Shear Moraines

Shearing appears to be the mechanism responsible for the formation of washboard moraines. The objections to marginal accumulations previously discussed are best explained by a shearing mechanism.

Elson (1957, p. 82) attributes the formation of washboard moraines to shearing of active ice over stagnant ice near the terminus in a receding glacier where surface ice-slopes are 5° to 10°. The shear planes transport subglacial debris to englacial and superglacial positions with a thickening of lodgment drift at the base of the shear. Elson suggests that thickening of the basal drift during shearing is responsible for the washboard-moraine ridges.

During the summer months, 35 to 50 feet of drift-free ice may melt (Lawrence and Elson, 1953, p. 100-101). Elson (1957, p. 82) suggests that the active thrust zone retreats as the brittle layer pinches out the plastic ice and widens the apron of stagnant ice. During the winter months, when little or no melting occurs, the thrust zone becomes more stationary, and accumulates a subglacial ridge of lodgment till. According to Elson, the thickening of lodgment till caused by thrusting of active ice over the stagnant ice in one season is insufficient to cause any appreciable advance of the basal part of the thrust zone. Therefore, the shear zone retreats in stages. Whether or not a ridge of lodgment till (washboard moraine) forms at the base of a thrust zone depends on the condition of the subglacial floor behind it; ridges may be discontinuous because conditions are not everywhere favorable for the ice to pick up subglacial debris.

There are several objections to a subglacial theory of origin for washboard moraines:

(1) Subglacial features are generally continuous and regular in shape, whereas washboard moraines are very irregular and discontinuous. During deposition of ablation drift, the surface morphology of the subglacial washboard moraines may be slightly modified but probably not enough to substantially modify the basic trend of the moraine.

(2) Washboard moraines often curve around potholes and sloughs (Fig. 8) or terminate at their boundaries (Fig. 8). If the moraines are primarily subglacial features it is difficult to explain this relationship.

(3) If subglacial thickening occurs by shearing, there should be a more consistent variation between the proximal and distal slope angles because stress is supplied primarily from one direction. The variation in slopes should be evident after deposition of a thin layer of ablation till if relatively uniform deposition occurs on both proximal and distal slopes.

(4) A subglacial theory does not easily account for washboard moraines crossing eskers.

(5) If washboard moraines are subglacial features, one might expect a better correlation of till fabrics between adjacent moraines.

Superglacial Shear Moraines

Shearing has been observed to produce superglacial shear moraines. Shear moraines are transverse debris-covered ridges, which have formed on the surface of the Greenland ice cap (Schytt, 1955, p. 57). Bishop (1957) investigated a number of shear zones in the Thule area in northwest Greenland and concluded that the shear moraines are formed by debris supplied by shear planes at the boundary between the stagnant outer zone and the active or mobile zone (Fig. 11).

Assuming that the ice sheet lies on an essentially horizontal subglacial floor and that the direction of ice movement is normal to the ice edge, shear moraines (Fig. 12) will form in the following manner (Bishop, 1957, p. 18):

(1) When the ice edge is no longer advancing but is in a general state of equilibrium, a narrow zone along the margin will be at a critical thinness at which plastic movement of the ice either cannot exist or is negligible compared with the interior. The outer stagnant zone acts as a barrier which impedes ice movement, so that high-angle imbricate shears develop as the mobile zone overrides the stagnant outer zone. At the ice surface these shears dip inland between 45° and 90° with the mean dip approximately 80°. These shears extend from the glacier floor toward the surface. During summer months, ablation occurs on the surface.

(2) When the ice margin no longer maintains a state of equilibrium, but is gradually retreating toward the interior, (ablation is exceeding accumulation) the contact between the stagnant outer zone and mobile inner zone recedes toward the interior so that new debris-carrying imbricate shears form inland from the first set. As ablation reduces the thickness of the ice, the debris in the shears melts out and provides a veneer on both sides of the shear planes.

(3) As the margin of the ice cap retreats, this sequence continues. More debris will have melted from the outer debris-carrying shears, so that the thickness of the morainal veneer on the ridges diminishes progressively away from the ice edge.

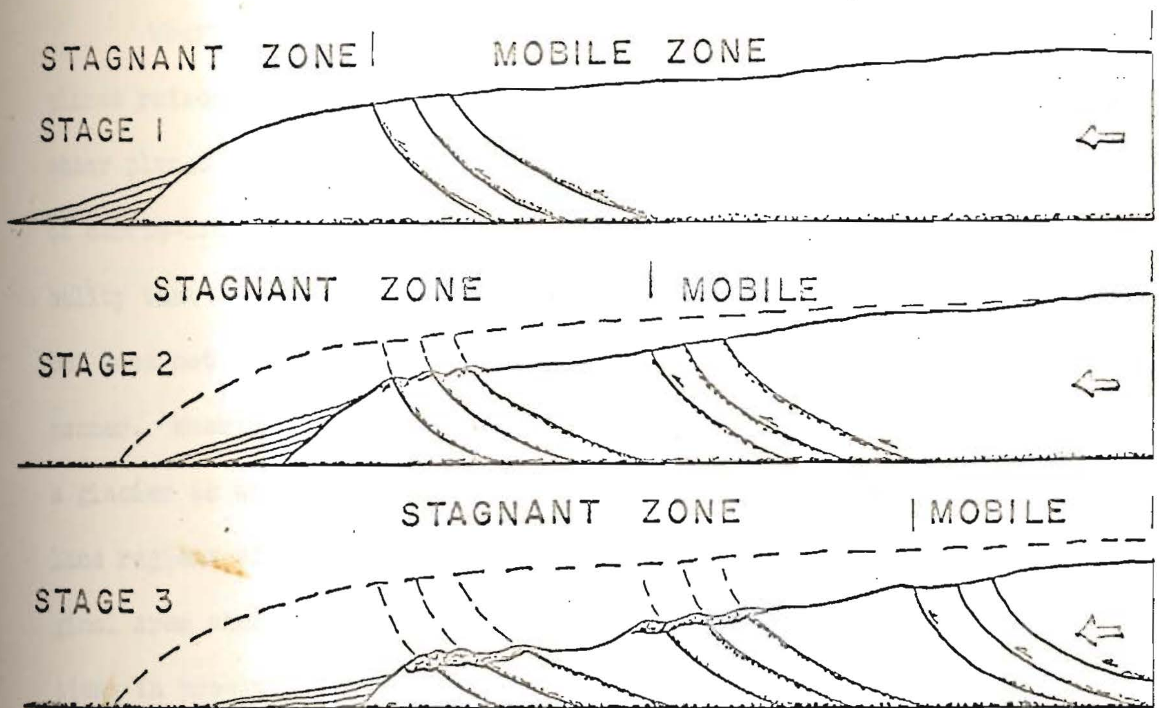


Figure 11. Diagram showing formation of successive shear moraines (Bishop, 1957, p. 18).

Figure 12. Aerial view along shear moraines near Thule, Greenland, taken from Bishop (1957, p. 8).

Weertman (1962, p. 2) stated that the composition of the shear planes raises a major criticism to Bishop's shear hypothesis. Some shear planes are composed of solid debris whereas others are composed of debris-laden ice up to 2 meters thick. Weertman accepts the possibility that ice can scrape layers of solid debris into a shear plane but does not believe that debris-laden ice could be formed in such a manner. Weertman proposes that debris can be frozen into the base of a glacier as water at the base of a glacier is frozen. Water from inland regions of the glacier moves under hydrostatic pressure to a marginal area where the ice cap is frozen to the ground. Slight variations in pressure and temperature cause a freeze-thaw cycle to occur that eventually will freeze debris into the ice. Debris probably cannot be frozen into the base of a temperate glacier because their marginal areas are not frozen to the ground.

Swinzow (1964) made a study of shear zones found in ice tunnels in the Greenland ice cap. He concluded that the formation of shear moraines at the edge of an ice sheet may be explained by the process of ablation. Two possible ideal conditions for shear moraine formation are considered by Swinzow (1964, p. 14):

(1) Ablation equal to ice advancement. Ice flow in the interior is essentially parallel to the surface. Ablation in marginal areas causes shear planes to become warped upward. A flow plane loaded with bottom material constitutes a shear plane. Where the condition becomes stabilized for a longer period in certain places, a large amount of debris accumulates along the edge of the ice surface and becomes a shear moraine. The height of a shear moraine ridge is the result of interaction between (a) liberation of rock debris from the ice

and consequent retardation of melting, and (b) the rate of removal by runoff.

(2) Amount of ice removed by ablation exceeds amount supplied. This results in a condition similar to the one described above. When ablation begins to affect the ice behind the chain of shear moraine ridges, a second set of shear planes may be formed farther away from the edge of the ice. Differential motion across the older shear planes ceases gradually, and new ones become more active.

Washboard moraines in North Dakota are probably remnant shear moraines similar to the type being formed in Greenland. A superglacial position is contrary to the origin proposed by Gwynne and Elson, but does correspond more closely with existing field information. Previous workers have failed to explain why (1) eskers and drumlinoid features are sometimes crossed by washboard moraines, (2) washboard moraine till fabrics appear to have no relationship with regional ice flow direction, and (3) there is no consistent variation between proximal and distal slope angles.

Ablation must exceed net accumulation in a retreating ice mass such as the one that formed the washboard moraines in North Dakota. A series of parallel shear zones will develop in such an ice mass (Swinzow, 1964, p. 14).

The abundance of washboard moraines in one area and the absence of them in adjacent areas suggest that their deposition is regulated by (1) the thickness of ablation drift, (2) the lithology of the basal drift, (3) the regimen of the ice margin, (4) the subglacial topography, (5) the angle of the debris-laden shear planes, and (6) the amount of post-glacial modification.

Thickness of ablation drift on stagnant ice is important because the rate of melting is dependent upon the insulation of the overlying drift. The effect of the reduced melting under a drift cover is to make the apron of stagnant ice wider and less steep.

Shear moraines would more likely be preserved during slow rather than rapid melting because of less catastrophic mass-wasting and deformation. The many small well-preserved eskers in northern Nelson County are evidence that the ice mass stagnated slowly and had a moderately thin ablation drift cover. If the drift was very thick, dead-ice moraine would probably have resulted.

Lithology of the basal till is important in the formation of shear moraines because the till ultimately reaches the ice surface and is subjected to mass-wasting. Highly plastic tills (high percentage of clay) will form very subdued moraines during deposition, whereas tills with low plasticity form moraines having greater relief and steeper slopes.

Unfavorable climatic conditions may affect the regimen of the ice margin in such a way that a stagnant zone may not be of the proper shape or geometry for debris-carrying shears to develop. In some cases, ablation may be so great that the shears might coalesce, forming a single moraine or a blanket of surface debris.

The angle of shear planes and the amount of debris contained in the shear planes will affect the size and shape of the shear moraine. Bishop (1957) indicates that the mean dip of the shear planes at the surface is approximately 80° inland. If the ice-cored shear moraine is directly superimposed over a debris-laden shear plane, debris in the shear plane will probably contribute to the surface shear moraine as the ice melts. In this way, shear moraines will vary in height in a particular region depending upon the amount of debris contained in shear planes.

Post-glacial modification is an important factor in the preservation of washboard moraines. If there is a high drainage density in a washboard moraine area, the ridges will be extensively modified and eroded. Absence of vegetation will also contribute to mass-movement thereby reducing relief.

If washboard moraines are remnant shear moraines deposited from a slowly melting stagnant ice sheet, washboard moraines that cross eskers and drumlinoid features can be explained. Subglacial and englacial eskers will be formed beneath the superglacial shear moraines, resulting in washboard moraines that cross eskers after deposition (Fig. 9). The same relationship probably applies to drumlinoid features crossed by washboard moraines.

A shear moraine origin might also explain the till fabrics found in northern Nelson County. No consistent preferred orientation relative to regional ice flow direction was found in these moraines. Shear moraine pebbles are preferentially oriented parallel to the dip of the shear (Bishop, 1957, p. 20). During deposition, the pebbles in the shear moraine and in the shear plane undoubtedly would become differentially modified. The till fabric orientations found in Nelson County presumably represent preferred orientations that have been depositionally modified.

Shear moraines occur on present-day valley glaciers in addition to ice caps. Elson (1957) observed transverse till ridges emerging from the Saskatchewan Glacier in Alberta and concluded that debris compressed in shear planes had been elevated into nearly vertical "dikes" of till as thick as 6 inches and several feet in height. When the supporting ice melted, the "dikes" slumped into ridges 1 to 2 feet high and 4 to 6 feet wide. Elson suggests that if this happened on a larger scale washboard moraine-like features would result, but the fabric probably would be destroyed due to slumping.

Transverse till ridges similar to those described by Elson occur near the terminus of the Athabasca Glacier, Alberta (Fig. 13).

Figure 13. Parallel shear moraines at the terminus of the Athabasca Glacier, Alberta. Note the coarse texture and low relief. View looking northeast.

The ridges are spaced from 30 to 50 feet apart and are approximately 3 to 4 feet high. A crude fabric analysis indicated a preferred orientation of pebbles parallel to direction of ice flow. From a total of 183 pebbles measured, 92 pebbles were found to be parallel, 26 pebbles transverse and 65 pebbles neither parallel nor transverse. The shear moraines were probably ice-cored; therefore, final settling had not yet occurred. The older shear moraines farthest from the terminus were the most indistinct as a result of melting of the probable core ice and modification by mass-wasting.

SUMMARY AND CONCLUSIONS

Washboard moraines in the past have been confused with similar transverse till ridges including ribbed moraines and De Geer moraines. Characteristics of northern Nelson County washboard moraines are as follows:

1. The moraines are generally 4 to 15 feet high, are spaced from 250 to 550 feet, and are discontinuous.
2. The moraines are subdued ridges generally paralleling each other; some bifurcate and merge with other washboard moraines.
3. Moraine slopes range from 2° to 6°.
4. Vegetation sometimes makes the washboard moraines indistinct on aerial photographs.
5. Some washboard moraines cross eskers and drumlinoid features. In some other cases, washboard moraines are truncated by eskers.
6. Washboard moraines curve around potholes and sloughs or terminate at their boundaries.
7. Compositional fabric analyses indicate unimodal, bimodal and polymodal distributions unrelated to regional ice flow direction.
8. The moraines are transverse to direction of ice flow.
9. The moraines are generally found associated with low-relief surface drift with poor drainage.

Previous studies failed to observe (1) eskers crossed by washboard moraines, (2) the fabric of washboard-moraine till is unrelated to regional ice-flow direction, (3) washboard moraines curving around potholes and sloughs or termination at their boundaries, and (4) the absence of variation in the proximal and distal slopes of washboard moraines. These observations suggest that washboard moraines were, prior to deposition, superglacial features rather than subglacial features as previously proposed by Elson (1957). Therefore, washboard moraines in North Dakota are interpreted to be remnants of superglacial shear moraines.

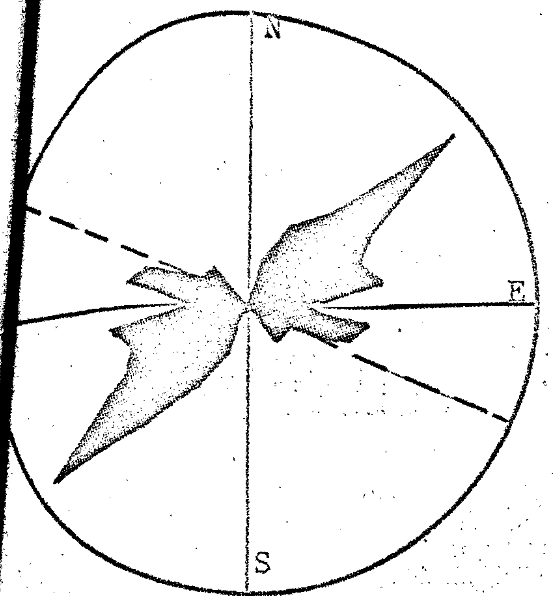
Considerably more glaciological investigation of shear zones is necessary before the superglacial shear moraine hypothesis of washboard moraine formation can be proven.

APPENDIX

ROSE DIAGRAMS OF WASHBOARD-MORAINE PEBBLE ORIENTATIONS

Twenty fabric analyses were made on fifteen washboard moraines in northern Nelson County. At each fabric site two-dimensional horizontal fabric analyses were made by measuring the directional orientation of pebbles in the till. Only the long axis of each pebble was measured and recorded. A minimum of fifty pebbles was measured at each site. The individual pebble measurements from each site were plotted, as rose diagrams, which appear in the following pages. The strike of each washboard moraine is indicated by a dashed line.

SITE 2



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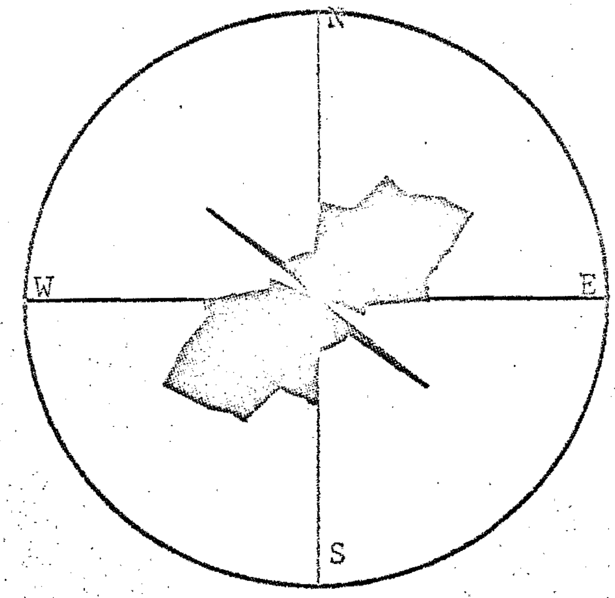
SITE 3



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Strike: N 90 W
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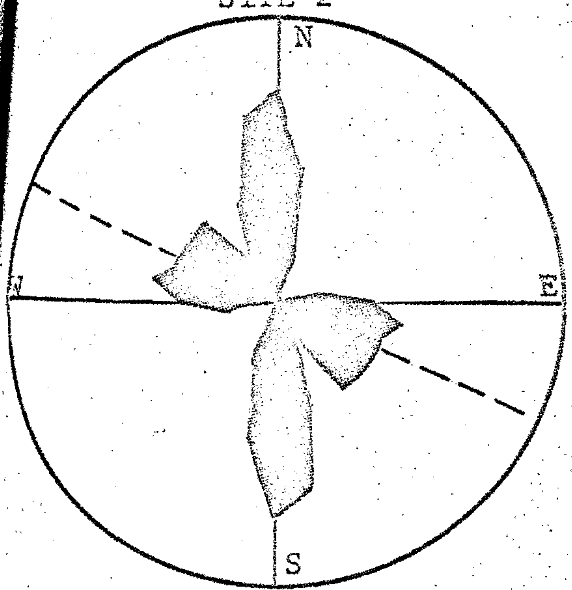
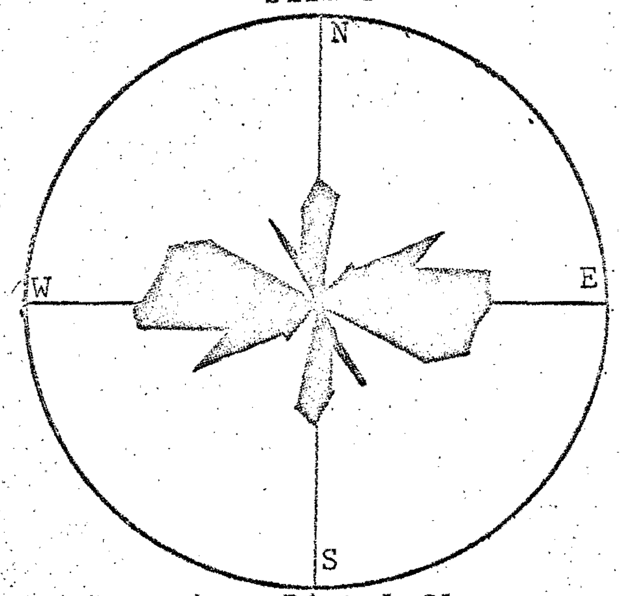
SITE 2



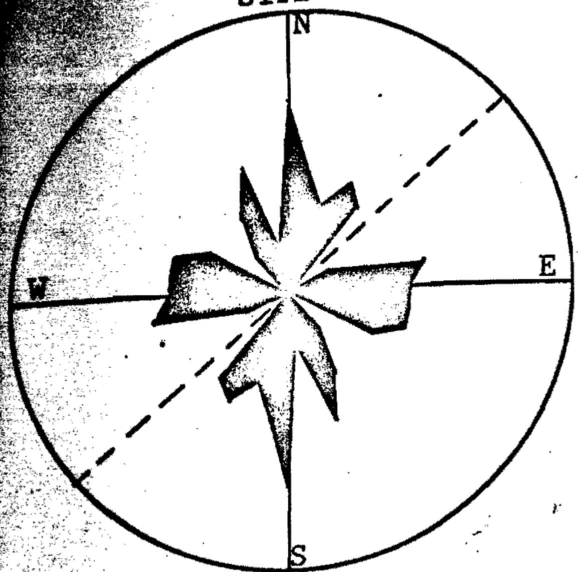
Location: Proximal Slope
Strike: N 65 W
n=50

SITE 3



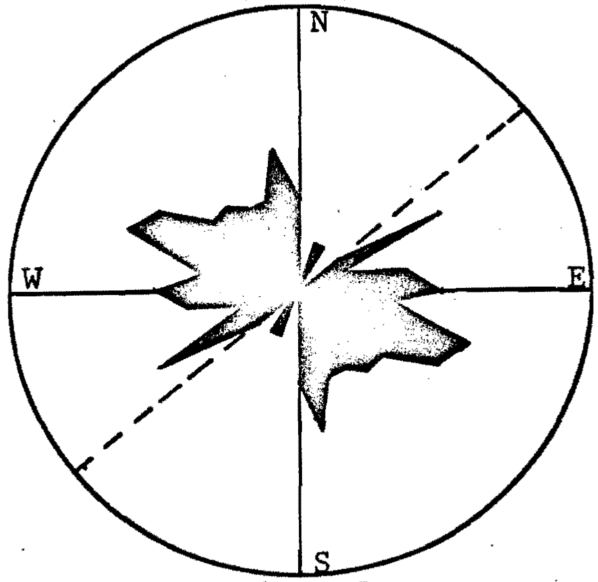
Location: Distal Slope
Strike: N 90 W
n=51

SITE 5



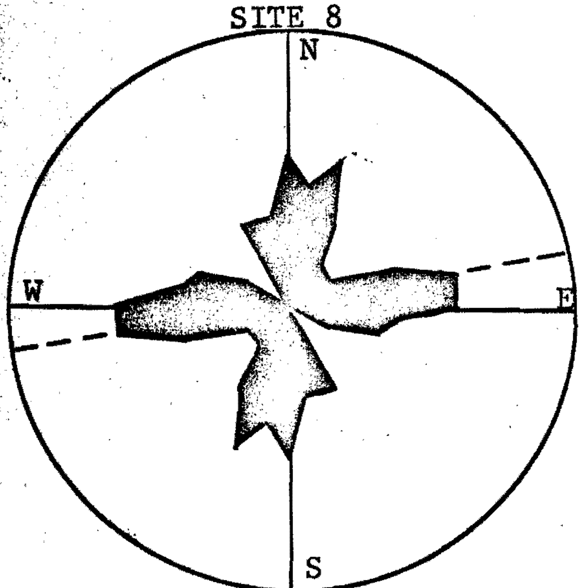
Location: Core
Strike: N 50 E
n=50

SITE 6



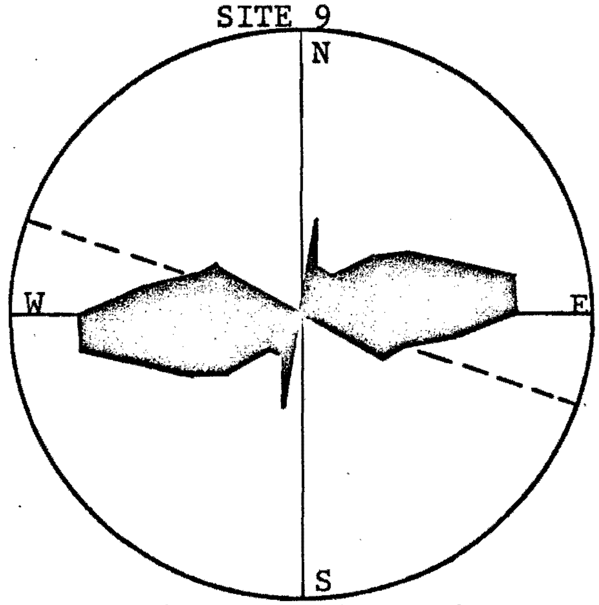
Location: Core
Strike: N 50 E
n=50

SITE 8



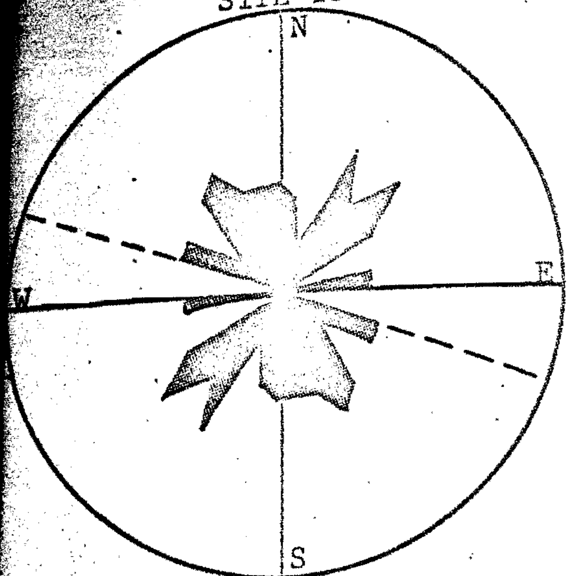
Location: Core
Strike: N 80 E
n=50

SITE 9



Location: Proximal Slope
Strike: N 70 W
n=51

SITE 10



Location: Core
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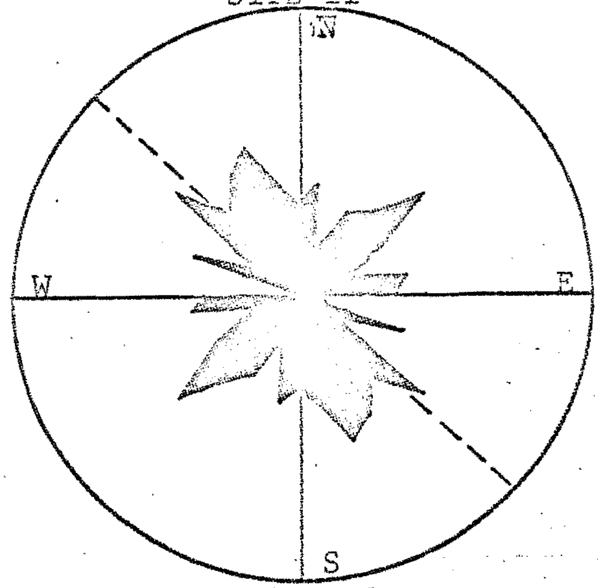
SITE 11



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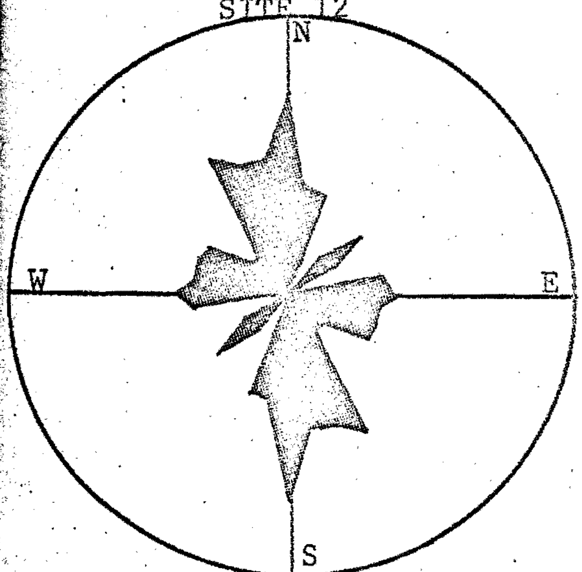
SITE 12



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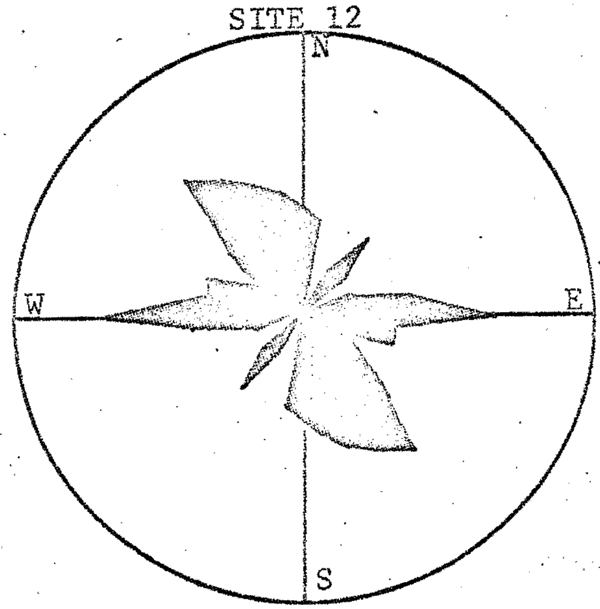

Location: Distal Slope
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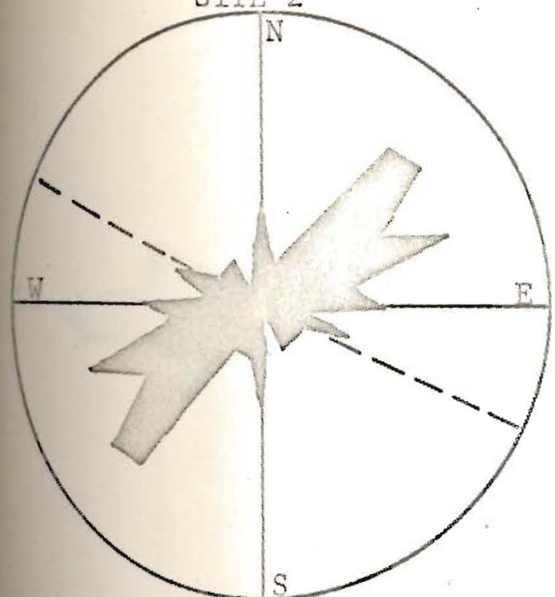

Location: Distal Slope
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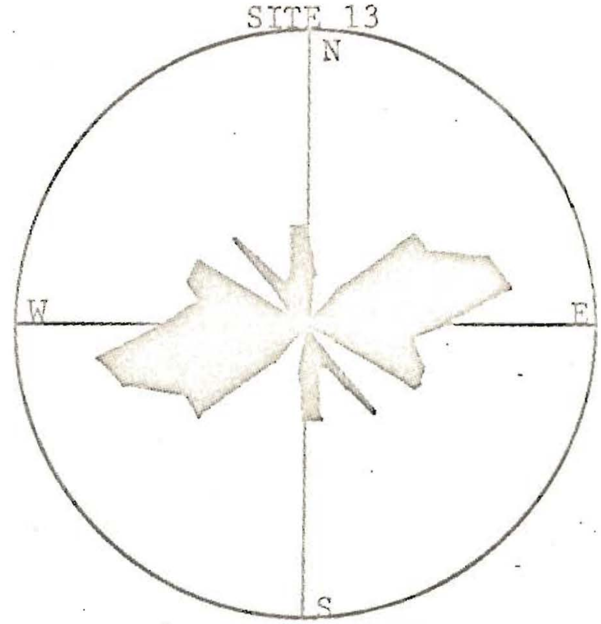
SITE 13



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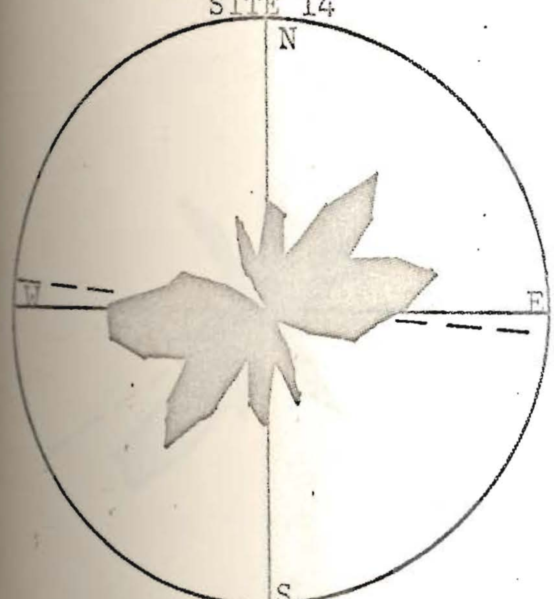
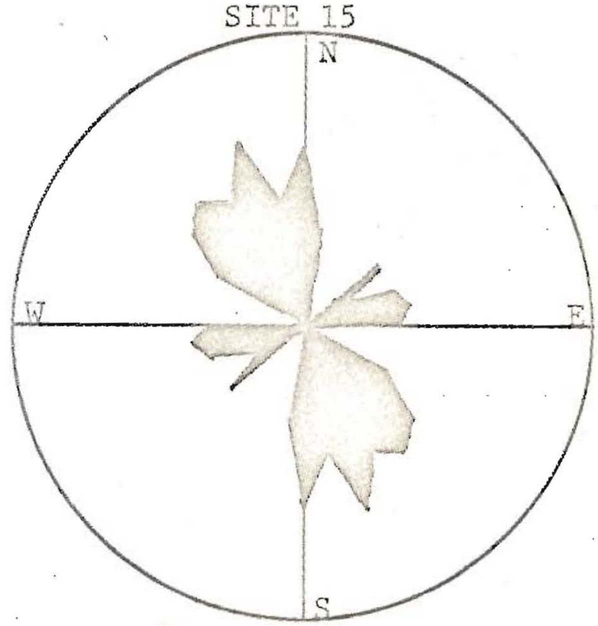
Strike: N 90 W
n=50

SITE 14



Location: Core
Strike: N 85 W
n=50

SITE 15



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Strike: N 90 W
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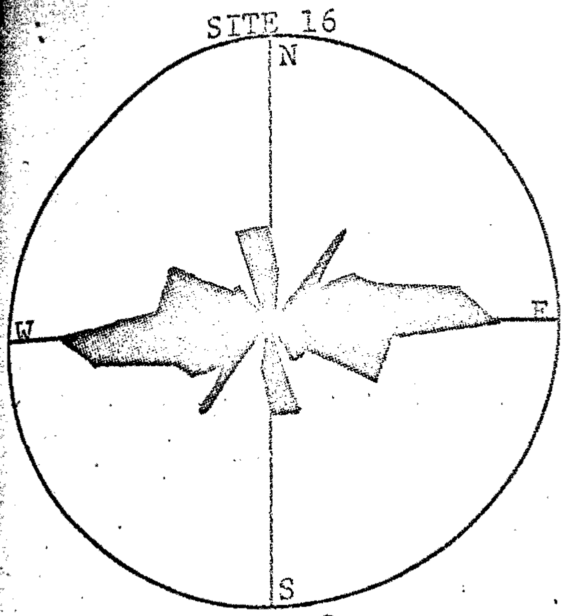
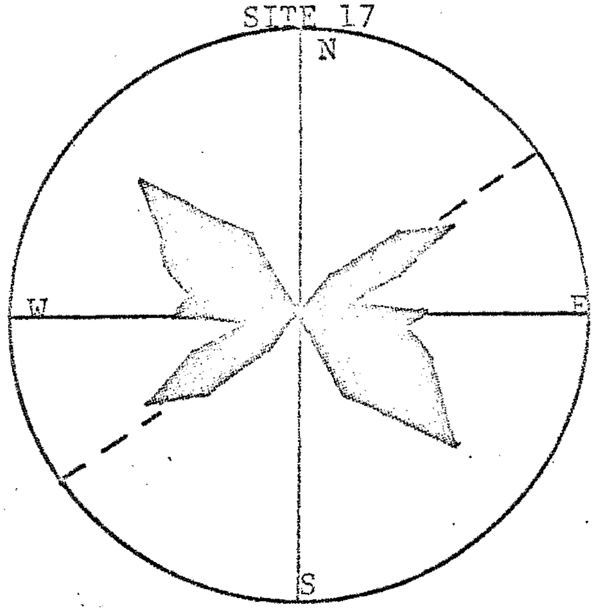


Location: Core
Strike: N 90 W
n=51



Location: Core
Strike: N 55 E
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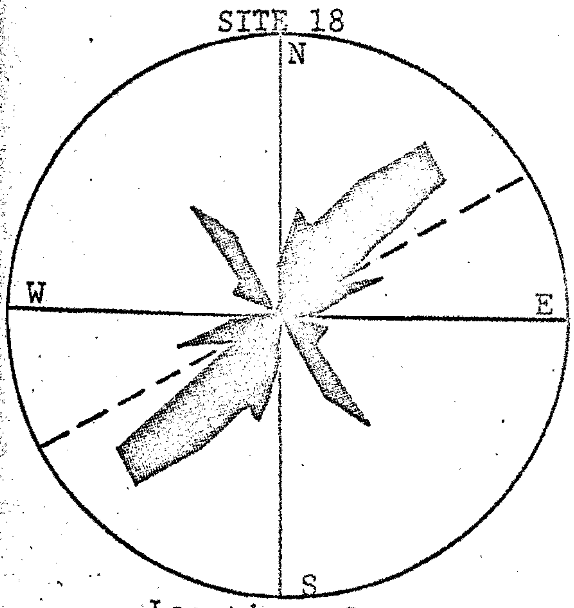
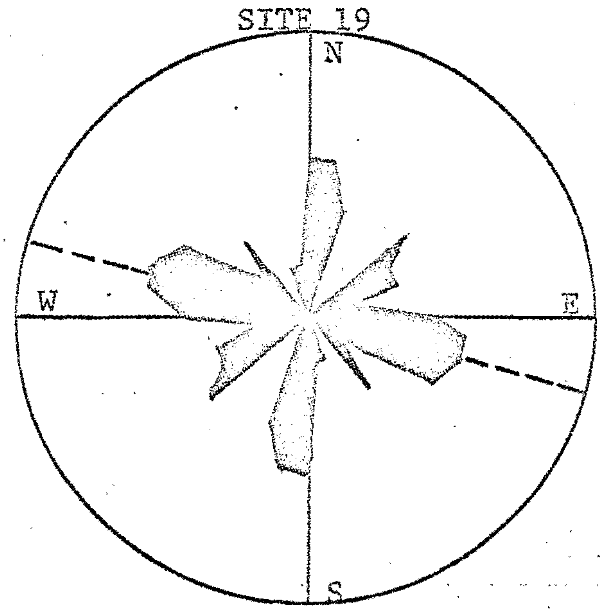


Location: Core
Strike: N 60 E
n=50



Location: Core
Strike: N 75 W
n=50

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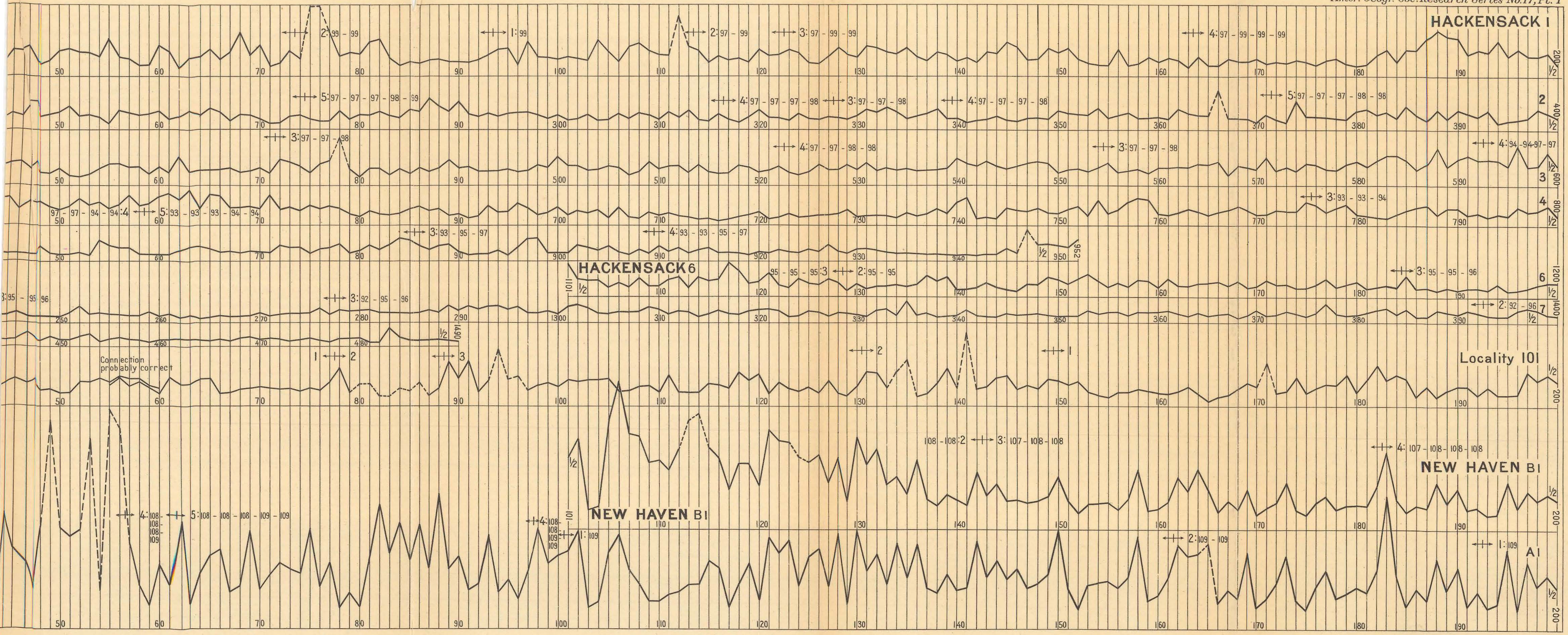
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Locality 101
NEW HAVEN B1
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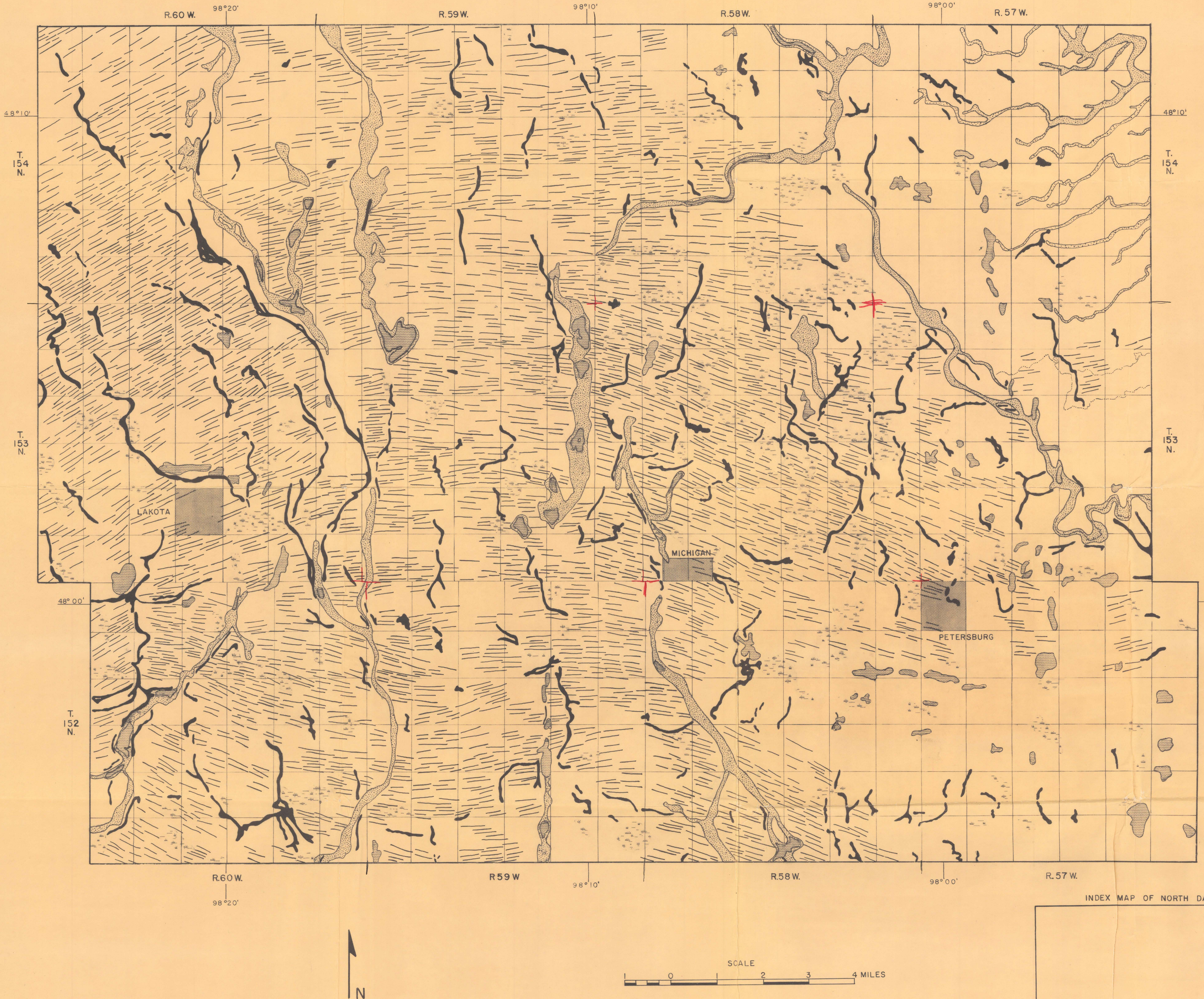
GLACIAL MAP OF NORTHERN NELSON COUNTY, NORTH DAKOTA



EXPLANATION

Ground Moraine. A gently undulating accumulation of till, with low constructional relief, generally less than 20 feet per square mile.

Meltwater, Buried, and Postglacial Channels. Linear depressions underlain by till or sand and gravel.

Lakes. Perennial and ephemeral.

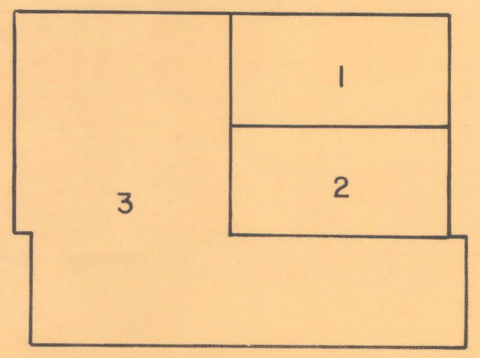
Sloughs. Perennial and ephemeral.

Eskers. Elongate and narrow ridges; sinuous or straight; may bifurcate; composed of glaciofluvial sand and gravel.

Kames. A mound or conical hill of drift; chiefly sand and gravel.

Washboard Moraines. Straight to arcuate low (less than 15 ft.) linear ridges of till, commonly concentrated in groups on ground moraine and which are perpendicular to direction of ice flow.

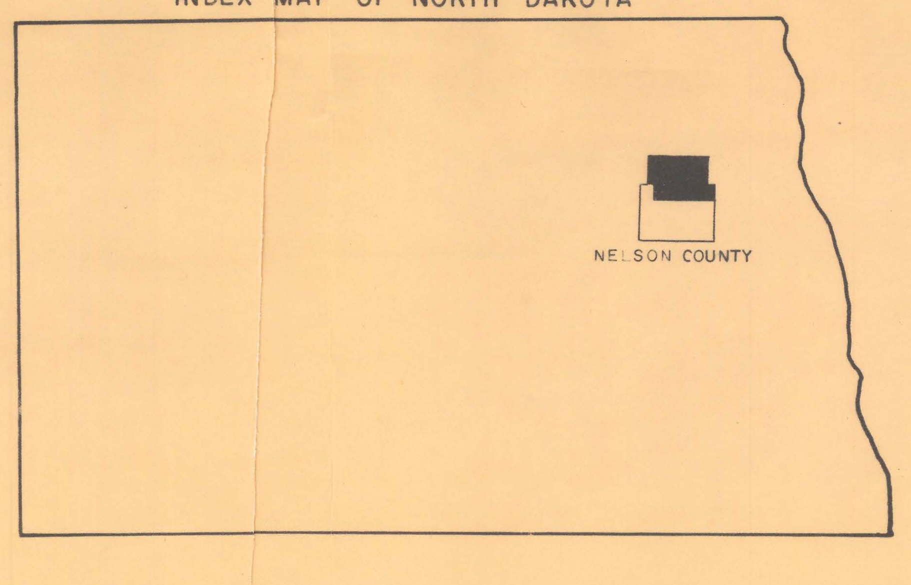
Ephemeral Streams.



GEOLOGY BASED ON MAPPING BY:

1) Roger J. Reede (1967)
2) Dennis N. Nielsen (1967)
3) Dennis N. Nielsen (1968)

INDEX MAP OF NORTH DAKOTA



D. Nielsen, M.A 1969